OPTICAL SPECTROMETER AND METHOD

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of United States Provisional Application No. 60/538,523 filed 1/22/2004.

FIELD OF THE INVENTION

[0002] This invention relates generally to the field of optical apparatus and in particular to an optical spectrometer and related method(s), suitable for use in single channel, or multiple-channel wavelength division multiplexed (WDM) communications systems or other optical systems.

BACKGROUND OF THE INVENTION

[0003] Optical communication systems oftentimes use wavelength-division multiplexing to increase transmission capacity. More specifically, a plurality of optical signals, each having a different wavelength, are multiplexed together into a WDM signal. The WDM signal is transmitted over a transmission line, and then subsequently demultiplexed so that individual optical signals may be individually received.

[0004] Successful implementation of high-speed WDM system depends upon the development of optical devices at reasonable cost. In particular, WDM systems, and other industries as well, require devices that provide the sorting and/or separation of wavelengths, for routing, measurement, or other purposes. One such device - an optical spectrometer and related method(s) – is the subject of the present invention.

SUMMARY OF THE INVENTION

[0005] I have invented an optical spectrometer and associated method(s) that offers a number of advantages over existing optical spectrometers and method(s).

[0006] Viewed from a first aspect, my invention is directed to an optical spectrometer method utilizing zeroth-order feedback to provide precise positional information.

[0007] Viewed from another aspect my invention is directed to an optical spectrometer apparatus that accepts a plurality of input signals and provides a plurality of output signals, and may utilize my inventive zeroth-order feedback.

[0008] Additional objects and advantages of my invention will be set forth in part in the description which follows, and, in part, will be apparent from the description or may be learned by practice of the invention.

BRIEF DESCRIPTION OF THE DRAWING

[0009] FIG 1 is a schematic representation of an optical arrangement according to the present invention;

[0010] FIG 2 is a schematic representation of an alternative embodiment of an optical arrangement according to the present invention;

[0011] FIG 3 is a schematic representation of an optical arrangement including position detection according to the present invention;

[0012] FIG 4(a-d) shows two alternative patterns (a-b) and the resulting output (c-d) of intensity vs. time respectively;

[0013] FIG 5 is a schematic representation of an alternative arrangement of an optical arrangement including position detection and a single lens according to the present invention;

[0014] FIG 6 is a schematic representation of an optical arrangement including a retroreflector;

[0015] FIG 7 is a block diagram of a control system useful with and according to the present invention; and

[0016] FIG 8 is a schematic representation of alternative mirror-grating configurations useful with, and according to the present invention.

DETAILED DESCRIPTION

[0017] With reference now to FIG 1, there is shown in schematic form an optical arrangement **100**, which exhibits our inventive teachings. More specifically, optical arrangement **100** depicts multiwavelength input signals carried on input fiber **110** being collimated by lens **120** and illuminating planar reflective diffraction grating **130** mounted on tip/tilt stage **140** capable of rotating the grating **130** about its X-axis or Y-axis. As can be appreciated, each wavelength of the multiwavelength input signals is diffracted into an angle corresponding to the wavelength.

[0018] While the input signals are shown in FIG 1 being carried on input fiber **110**, it is understood that the input could be another type of optical waveguide, besides an optical fiber, or it could be a free-space aperture. Preferentially, the intensity profile of light in the input aperture is single-lobed, and the input numerical aperture is matched to the numerical aperture of the optics used in the optical apparatus..

[0019] Diffracted signals **115** are focused by a second pass through lens **120** and are imaged onto a permanent spectral-plane spatial filter that passes a portion of the imaged spectrum and blocks the rest. As can be readily appreciated, a broad-spectrum multi-channel signal would be imaged into a continuous column of spots on the face of the permanent spectral-plane structure.

[0020] Those portions of diffracted wavelength signal **115** which are imaged onto the opaque region and are absorbed or reflected, while the portions of wavelength signal **115** that are imaged onto the transparent aperture **170** are transmitted to illuminate an optical power detector **160** located immediately behind the aperture.

[0021] In operation, the tip/tilt stage **140** is controlled through electrical connections **145**. Rotating tip/tilt stage **140** around its X-axis will steer the dispersed spectral pattern illuminating the permanent spectral-plane structure to shift vertically, and modify the center wavelength of the signal entering detector **160**. In this exemplary embodiment shown in FIG 1, the width of the aperture in the y-direction varies along the x-direction. Rotating stage **140** around its Y-axis will cause the dispersed spectral pattern illuminating the spectral-plane filter to shift laterally (as drawn, into and out of the page), and modify the wavelength bandwidth of the signal entering detector **160**. As can be appreciated, with this optical arrangement, the signal can be completely blocked from the photodetector by rotating the stage about the Y-axis so that the dispersed spectrum completely misses the aperture so that the photodetector dark current can be measured and subtracted from the signal current.

[0022] With reference now to FIG 2, there is shown an arrangement substantially similar to that shown in FIG 1, in which a plurality of multiwavelength signals enter the system at input points arrayed along the x axis **210[1] ... 210[N]**. Each of these inputs is imaged on the spectral plane filter structure **250** as a separate wavelength-dispersed column along the y direction. With this arrangement, the length of the aperture **270** in the x direction may be chosen such that only one column illuminates the aperture at a time. By rotating the stage about the x axis, the spectrum of one input signal is measured. By rotating the stage about the y-axis, a different signal illuminates the aperture so that its spectrum can be measured.

[0023] An alternative optical arrangement exhibiting additional aspects of my inventive concepts is shown schematically in FIG 3. Shown therein is input **310**, lens **320**, grating **330** positioned on tip/tilt stage **340**, spectral plane device **360** having aperture **370**, and position detecting system including lens **380** and position detector **390**.

[0024] With continued reference to FIG 3, a multiwavelength input signal carried on input fiber **310** is collimated by lens **320** and illuminates planar reflective diffraction grating **330** mounted on tip/tilt stage **340** which, through its operation, rotates the grating about its X-axis or Y-axis, as desired. As described earlier, each wavelength signal beam is diffracted into an angle corresponding to its wavelength. Diffracted signals are focused by a second pass through lens **320** and are imaged onto a permanent spectral-plane device **360** having an exit slit aperture **370**.

[0025] Provided that the system shown in the optical arrangement of FIG 3 is mechanically stable, the wavelength of light centered on the exit slit aperture **370** is uniquely determined by the angle θ (**347**) of the grating **330**. A drive signal V_d (not shown), which may be applied to tip/tilt stage electrical connectors **345**, rotates the grating through angle θ according to a function $\theta(V_d)$. Upon calibration of the system, a correspondence can be determined between V_d and center wavelength $\lambda(V_d)$ passing through the exit slit, so that the spectrum can be determined from a synchronous measurement of drive signal and photocurrent which may be measured at the exit slit **370**. Unfortunately, however, $\theta(V_d)$ may not be completely stable -- it may depend on environmental factors or may drift over time due to aging processes. Moreover, the function may be frequency dependent. Thus, a separate means of measuring θ is helpful.

[0026] As can be appreciated by those skilled in the art, the diffraction grating **330** disperses light into multiple orders. Additionally, the grating is designed to have high efficiency in one non-zeroth order, and this order is used for the spectral measurement. That fraction of the light diffracted into the zeroth-order may be used to measure the position of the stage.

[0027] In Fig. 3, the zeroth order reflects off the grating and is collected by a lens **380**. As will be shown subsequently, the lens may advantageously be the same as that lens collecting the signal **320** or it may be a different lens. In this specific embodiment

shown in FIG 3, the zeroth-order-collecting lens **380** is physically distinct from the signal-collecting lens **320**.

[0028] The collecting lens **320** images the zeroth order beam **395** onto a position detector **390**. It will be obvious to those skilled in the art that a curved mirror (not shown) could be used in place of the lens or the grating could have optical power to image the zeroth-order beam **395** onto the position detector **390**. Furthermore, and depending on the type of position detector used, the lens **380** may be omitted.

[0029] For the zeroth-order beam, the angle of reflection from the grating is independent of wavelength. Consequently, all wavelengths comprising the zeroth-order beam **395** are imaged to a common spot on the position detector **390**. Thus, the position of the spot on the position detector **390** is uniquely determined by the position of the grating **330**. The position detector **390** may comprise a quad-cell or bi-cell detector or a "position-sensitive detector" (PSD). Alternatively, it may include a single photodetector that may be covered by a series of apertures.

[0030] Elements of such a position detector are shown in FIG 4. With reference to that figure, a single photodetector, for example, is positioned behind an opaque screen **4a** having a series of transparent slits arranged in a periodic pattern. As a grating, such as that shown in FIG 3 by reference numeral **330**, is tilted around the x-axis, the zeroth-order spot travels horizontally to the right across the slits on the opaque screen **4a**, thereby producing a series of peaks that register in the photocurrent $I_{position}$ in a manner such as that shown in FIG **4c**.

[0031] Concurrently, and as a result of the grating being tilted, the dispersed spectrum passes across the single exit slit such as that shown prior in FIG 3 as reference numeral **370** and now in FIG **4b**. In this example, and as noted before, the signal comprises 3 wavelength signals. The relative power of each signal is indicated by the relative powers of the peaks 1, 2, and 3 in the plot of I_{signal} v. time that is shown in Fig. **4d**.

[0032] Through calibration, the correspondence between the temporal registration of the position signal and the peak transmittance of each signal wavelength onto the signal detector can be determined. This correspondence is only unique over a wavelength range $\Delta\lambda$ that is scanned during the time it takes the zeroth-order spot in **4a** to traverse one period of the position detector screen. If the uncertainty in $\lambda(V_d)$ is less than $\Delta\lambda$, then advantageously, the spectrum may be uniquely determined according to our inventive teachings by synchronous measurement of $I_{position.}$, I_{signal}, and V_d.

[0033] With these inventive teachings in place, alternative embodiments may now be shown. One such alternative embodiment is shown in FIG 5, which shows an optical arrangement where a grating is fixed, and a tip-tilt mirror in positioned close proximity to it. Additionally, the two lenses utilized in the example shown earlier with FIG 3, is now reduced to a single lens.

[0034] With specific reference now to that FIG 5, a multiwavelength signal emerges from optical input **510**, which may include an optical fiber or other suitable structures, and is collimated by lens **520** which further directs the signal to mirror **543** that is positioned on tip/tilt stage **540**, which is controllably tiltable by applying appropriate signals to electrical contacts **545**. Signals reflected from the mirror **543** are directed to a fixed grating **530**.

[0035] As noted in my discussion of the two-lens configuration of FIG 3, the diffraction grating **530** disperses light into multiple orders and the grating is designed to have high efficiency in one non-zeroth order, and this high-efficiency non-zero order is used for the spectral measurement. That fraction of the light diffracted into the zeroth-order may advantageously be used to measure the position of the stage.

[0036] In this example shown in FIG 5, the zeroth-order diffracted beam **595** passes through and is focused by the same lens **520** as the multi-wavelength signal emerging from optical input **510**. More specifically, the zeroth-order diffracted beam **595** is focused by the lens **520** onto a position detector **590.** Simultaneously, the non-zeroth order is diffracted onto the mirror **543**, where it is further reflected through lens **520** and focused onto slit **570** within spectral plane structure **560**. Such a compact structure, can advantageously offer numerous design alternatives.

[0037] FIG 6 shows an exemplary double-pass monochrometer constructed according to my inventive teachings. Similar to that shown in FIG 1, and with reference to FIG 6, **600**, multiwavelength input signals carried on input fiber **610**, and are

collimated by lens **620** such that they illuminate planar reflective diffraction grating **630** mounted on tip/tilt stage **640** capable of rotating the grating **630** about its X-axis or Y-axis.

[0038] The diffracted signals are focused by a second pass through lens **620** at the mid point of folded retroreflector **605**. The retroreflector **605** reflects the signals back through lens **620**, which collimates the beam and directs it onto diffraction grating **630** for the second time. The signals are further diffracted by grating **630** and imaged by lens **620** onto a permanent spectral-plane spatial filter **650**, having aperture **670**. Those portions of the diffracted wavelength signal that are imaged onto the aperture **670** are transmitted to illuminate an optical power detector **660** or other device located immediately behind the aperture.

[0039] As can be seen from this arrangement, after one pass through the system, the signal is retro-reflected, through the action of retroreflector **605** about the axis perpendicular to the direction of dispersion so that the spectrum is inverted. The second pass through the system further disperses the signal so that the resolution of the system is effectively doubled. Furthermore, a spatial filter (not shown) may be inserted at the retroreflector **605** to filter out all but a band of wavelengths, thereby reducing the background light produced by omnidirectional scattering off the grating **630** in the second pass. The retroreflector **605** itself will perform spatial filtering if its clear aperture **606** is smaller than the length of the dispersed spectrum in the spectral plane.

[0040] With these inventive structures and methods in place, one can quickly appreciate the benefits that various modifications or particular implementations of my teachings will produce. In particular, and with reference now to FIG 2, one will recall the optical apparatus **200** in which a plurality of multiwavelength signals enter the system at input points arrayed along the x axis **210[1] ... 210[N]**. Each of these inputs is imaged on the spectral plane filter structure **250** as a separate wavelength-dispersed column along the y axis. With this arrangement, the length of the aperture **270** in the x direction may be chosen such that only one column illuminates the aperture at a time. By rotating the stage about the x axis, the spectrum of one input signal is measured. By rotating the stage about the y-axis, a different signal illuminates the aperture so that its spectrum can be measured.

[0041] With that reference to that FIG 2 in mind and with reference now to FIG 7, the tip/tilt stage **240** may be periodically modulated in angle about the y-axis such that the optical signal spectrum received from one of the inputs **210[1]...210[N]**, and imaged on the spectral plane filter **250** periodically moves on and off the aperture **270**, thereby "chopping" the imaged signal. Chopping, in combination with synchronous detection using a lock-in amplifier is but one technique for improving the signal-to-noise ratio in measurements systems. In particular, the dark current of the photodetector **260** and the 1/f noise of the amplifier can be reduced this way.

[0042] A simplified block diagram of such a detection scheme is shown in FIG 7. Specifically, optical spectrometer **710**, utilizes functional input **730** to drive y-axis of the tip/tilt stage (not shown), produces I_{signal} which is supplied as input to transimpedance

amplifier **720,** the output of which subsequently drives lock-in amplifier **740** in conjunction with functional input **730** to produce output signal **750** having the more desirable noise characteristics.

[0043] With reference to FIG 8, there is shown illustrative alternative arrangements for grating/mirrors as may be used with my invention. In FIG 8(a), the input signal **810** is diffracted from stationary reflective diffraction grating **820** and illuminates mirror **830** that is positioned on tip/tilt stage **840** such that it is controllably tiltable by applying appropriate control signals through contacts **850**. Mirror **830**, is oriented such that a reflected signal is incident on reflective diffraction grating **820** where it is diffracted a second time. As can be appreciated, this configuration provides approximately twice the change in output angle as a function of input wavelength (spectral dispersion) as compared with configurations not exhibiting this "double diffraction".

[0044] Additionally, with reference to FIG 8(a), shown therein are both zeroth-order **812** and non-zeroth-order **814** signals (in this example they are labeled as "1st order") reflected from the surface of the grating **820.** As noted prior, the zeroth-order signal **812** is used to determine/measure positional information about the movable element (in this instance, the mirror **830**). The non-zeroth-order signal **814**, is directed to an output which may be an optically useful aperture or other output such as a slit, whether uniform, tapered, stepped or varying, depending upon the particular nomenclature used.

[0045] FIG 8(b) is an additional variation in which input signal **815** is diffracted in passing through transmissive diffraction grating **825** then is incident upon first surface mirror **835** also mounted on tip/tilt stage **845**. The reflected signal is diffracted again by a second pass through the transmissive grating **825** thereby producing output, first-order signal **819**. Similar to that shown for the discussion of FIG 8(a), in this FIG 8(b) both zeroth-order **817** and non-zeroth-order **819** signals are shown. As before, the zeroth-order **817** signals are used to determine positional information about the movable element (in this example, the mirror **835**) and the non-zeroth-order **819** signals are directed to a suitable optical output. Lastly, while the non-zeroth-order **819** signals are shown labeled as "1st order", our invention is not so limited and other order signals may be directed to output(s) as well.

[0046] Of course, it will be understood by those skilled in the art that the foregoing is merely illustrative of the principles of this invention, and that various modifications can be made by those skilled in the art without departing from the scope and spirit of the invention. Accordingly, my invention is to be limited only by the scope of the claims attached hereto.

WHAT IS CLAIMED IS: